Compact Holographic Data Storage System

T. H. Chao, H. Zhou, , G. Reyes, D. Dragoi, and J. Hanan
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Abstract- An innovative compact holographic data storage (CHDS) system will be presented. This system utilizes a new electro-optic (E-O) beam steering technology to achieve a design goal of up to 250 Gbs in a cubic photorefractive crystal with up to 1 Gbs/sec transfer rate.

I. INTRODUCTION

NASA's future missions would require massive high-speed onboard data storage capability to support Earth Science missions. With regard to Earth science observation, a 1999 joint Jet Propulsion Laboratory and Goddard Space Flight Center (GFSC) study ("The High Data Rate Instrument Study" [1]) has pointed out that the onboard science data (collected by high date rate instruments such as hyperspectral and synthetic aperture radar) stored between downlinks would be up to 40 terabits (Tb) by 2003. However, onboard storage capability in 2003 is estimated at only 4 Tb that is only 10% of the requirement. By 2006, the storage capability would fall further behind that would only be able to support 1% of the onboard storage requirements.

Current technology, as driven by the personal computer and commercial electronics market [2], is focusing on the development of various incarnations of Static Random Access Memory (SRAM), Dynamic Random Access Memory (DRAM), and Flash memories. Both DRAM and SRAM are volatile. Their densities are approaching 256 Mbits per die. Advanced 3-D multichip module (MCM) packaging technology has been used to develop solid-state recorder (SSR) with storage capacity of up to 100 Gbs [3]. The Flash memory, being non-volatile, is rapidly gaining popularity. Densities of flash memory of 256 Mbits per die exist today. High density SSR could also be developed using the 3-D MCM technology. However, Flash memory is presently faced with two insurmountable limitations: Limited endurance (breakdown after repeated read/write cycles) and poor radiation-resistance (due to simplification in power circuitry for ultra -high density package).

It is obvious that state-oft-the-art electronic memory could not satisfy all NASA mission needs. It is necessary to develop new memory technology that would simultaneously satisfy non-volatility, rad-hard, long endurance as well as high transfer rate, low power, mass and volume to meet all NASA mission needs.

JPL, under current sponsorship from NASA Earth Science Technology Office, is developing a high-density, nonvolatile and rad-hard Compact Holographic Data Storage (CHDS) system to enable large-capacity, high-speed, low power consumption, and read/write of data for potential commercial and NASA space applications [3-4]. This AHM consists of laser diodes, photorefractive crystal, spatial light modulator, photodetector array, and I/O electronic interface. In operation, pages of information would be recorded and retrieved with random access and high-speed. The nonvolatile, rad-hard characteristics of the holographic memory will provide a revolutionary memory technology to enhance the data storage capability for all NASA's Earth Science Missions.

In this paper, to date accomplishments in developing this CHDS at JPL will be presented. A recent experimental demonstration of holographic memory storage/retrieval will also be described.

II. ADVANCED HOLOGRAPHIC MEMORY WITH ANGULAR MULTIPLEXING SCHEME USING LIQUID CRYSTAL BEAM STEERING DEVICES

The AHM system architecture, as shown in Figure1, consists of a writing module for multiple holograms recording and a readout module for hologram readout. The writing module includes: a laser diode as the coherent light source, a pair of cascaded beam steering Spatial Light Modulators (BSSLM), one transmissive and one reflective in each pair, for angular multiplexed beam steering, a Data SLM for data input for storage; two cubic beam splitters for beam forming; and a photorefractive (PR) $LiNbO_3$ crystal for hologram recording. The readout module also shares this photorefractive crystal. The readout module includes: a laser diode with the same wavelength as the writing one; a pair of cascaded BSSLMs to generate phase conjugated readout beam (i.e. the readout beam is directed opposite to that of the writing beam); the shared photorefractive crystal; a cubic beam splitter; and a photodetector array for recording the readout holograms The system uses an angle multiplexing scheme to store multiple holograms and phase-conjugated beams to readout each hologram.

In hologram writing, the collimated laser beam (top left in Fig.1) splits into two parts at the first cubic beam splitter

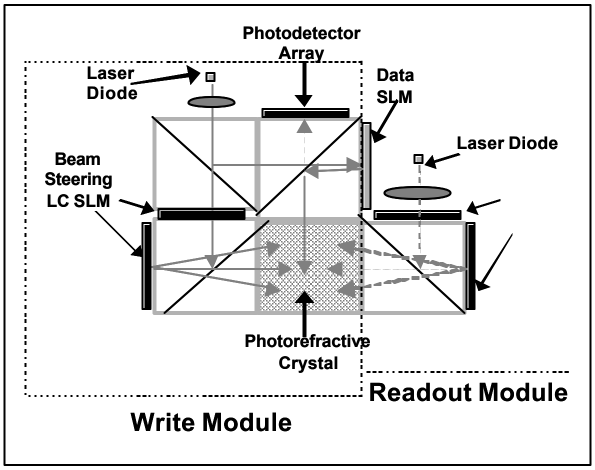

Figure 1. System schematic architecture of an Advanced Holographic Memory

and then: 1) The horizontally deflected light will travel across the second cubic beam splitter to read out the input data after impinging upon the Data SLM. The data-carrying beam will then be reflected into the PR crystal as the data-writing beam. 2) The remaining part of the laser beam will go through vertically, passing a BSSLM and then reflected to the second reflective BSSLM. Both BSSLMs are 1-D blazed phase gratings capable of beam steering with an angular deflection determined by the grating periods. By cascading two BSSLMs in orthogonal, 2-D beam steering can be achieved (in the future, only a single 2-D beam steering SLM will be needed). This deflected laser beam will then be directed toward the PR crystal as the reference-writing beam. It will meet the data carrying writing beam inside the PR crystal to form an interfering grating (hologram). Each individual hologram is written with a unique reference angle and can only be readout at this angle (or its conjugated one). By varying the reference beam angle in sequential recording, a very large number of holograms can be recorded in the recording medium.

For hologram readout, we have devised an innovative phase conjugation architecture. This phase conjugation scheme will enable lensless hologram readout with minimal distortion (low bit error rate). As shown in Fig.3, a second pair of transmissive and reflective BSSLMs combination will be used to provide a phase-conjugated readout beam (with respect to the writing reference beam). After the beam impinges upon the PR crystal, the diffracted beam from the recorded hologram will exit the PR crystal backtracking the input data beam path, due to the phase-conjugation property. It then directly impinges upon the photodetector array without the need for focusing optics and reconstructing the corresponding data page, as was recorded and stored in the PR crystal

A. *Beam Steering Spatial Light Modulator*

JPL has recently collaborated with the Boulder Nonlinear System Co. (BNS) to develop a BSSLMS. This device is built upon a VLSI back plane in ceramic PGA carrier. A 1-dimensional array of 4096 pixels, filled with Nematic Twist Liquid Crystal (NTLC), is developed on the SLM surface. The device aperture is of the size of 7.4 mm x 7.4 mm, each pixel is of 1 mm x 7.4 mm in dimension. Currently, the response time can reach 200 frames/sec. In the future, by replacing the NTLC with Ferroelectric Liquid Crystal (FLC), the speed may be increased by at one order of magnitude (i.e. > 2000 frames/sec). A photo of this BSSLM is shown in Figure 2.

The principle of operation of this BSSLM is illustrated in Figure 3. Since the SLM is a phase-modulation device, by applying proper addressing signals, the optical phase profile (i.e. a quantized multiple-level phase grating) would repeats over a 0-to-2π) ramp with a period d. The deflection angle q of the reflected beam will be inversely proportional to d:

$$q = \sin^{-1}\left(l/d\right)$$

Where λ is the wavelength of the laser beam. Thus, beam steering can be achieved by varying the period of the phase grating

The diffraction efficiency, η, of this device is

$$h = \left(\frac{\sin\left(p/n\right)}{p/n}\right)^2$$

Where n: number of steps in the phase profile. For example h ~ 81% for n =4, and h ~95% for n =8.

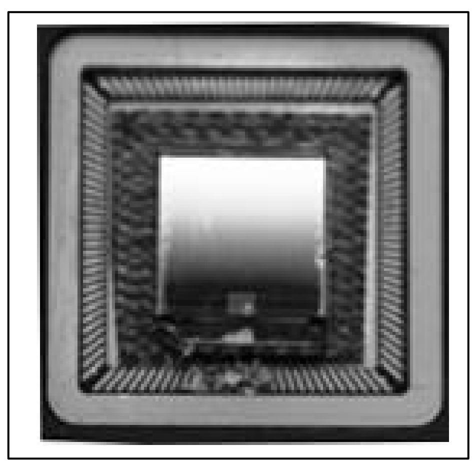

Figure 2. Photograph of a 1 x 4094 Liquid Crystal Beam Steering SLM

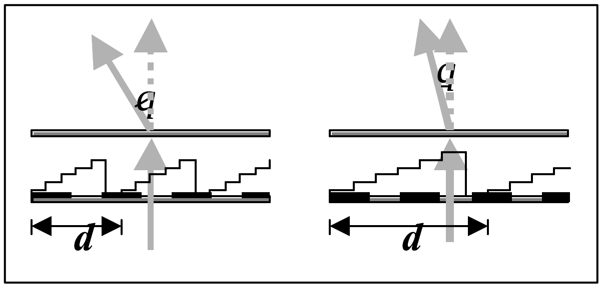

Figure 3. Beam steering achieved by controlling the phase profile across a BSSLM.

Number of resolvable angles can be defined by:

$$M = 2m / n + 1$$

Where m is the pixel number in a subarray, and n is the minimum number of phase steps used. For example, M = 129 for m=512, n =8 with a 1 x 4096 beam steering device.

III. AHM BREADBOARD AND EXPERIMENTAL DEMONSTRATION

We have developed a CHDS breadboard according to the architecture as shown in Figure 1. A photograph of this breadboard is shown in Figure 4. This breadboard is of a book-size (e.g. a telephone book). Main devices included in this AHM breadboard has been identified in Figure 4. We have to date, implemented a 1-D scanning scheme using a single BSSLM. This device has enabled us to record 128 resolvable holograms. We have also developed a LabView based system controller that has enabled us to perform holographic data recording/retrieval in a autonomous manner.

We have successfully performed holograms record/retrieval demonstrations using this breadboard. During this experiment, we have utilized a set of grayscale images of the near earth asteroid, Toutatis, as the input. A few retrieved images from the holograms recorded in the $LiNbO_3$, presenting the Toutatis viewed in several aspect angles, are shown in Figure 5.

In the next step, a pair of this BSSLM will be cascaded to enable 2-D scanning of the reference beam to increase the number of stored holograms. This 2-D beam multiplexing would result in a total of 11,520 resolvable scanning angles. Thus it will enable the storage of more than 11,000 pages of holographic data with in a 1-cm3 volume of PR crystal. The total storage capacity, with using a 1000 pixel x 1000 pixel input page would exceed 10 Gbs. Further increase the input frame size (e.g. 5000 pixel x 5000 pixel) would further increase the memory size to 250 Gbs. The

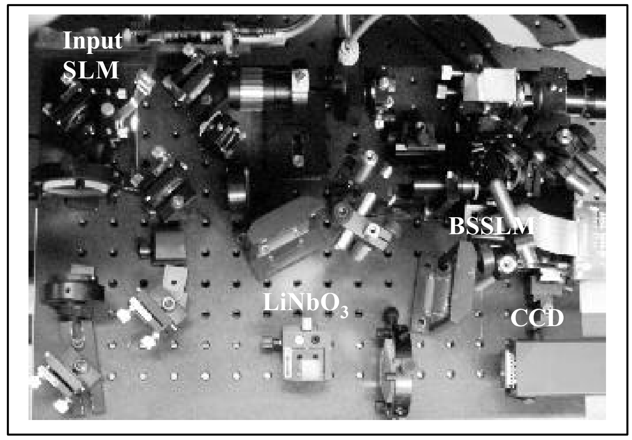

Figure 4. A book-sized CHDS breadboard under development at JPL

potential of stacking a multiple of very compact holographic memory cubes on a memory card (e.g. 10 x 10 cubes on each card) will provide up to 1 terabits storage capacity per card. The transfer rate ranges fro 200 Gbs/sec (with Nematic liquid crystal BSSLM) to 2000 Sec/sec (with Ferroelectric liquid crystal BSSSLM). In summary, primary advantages of this holographic memory system include: high storage density, high transfer rate via randomly accessible E-O beam steering, compact and ruggedness, low voltage and low power consumption.

ACKNOWLEDGMENT

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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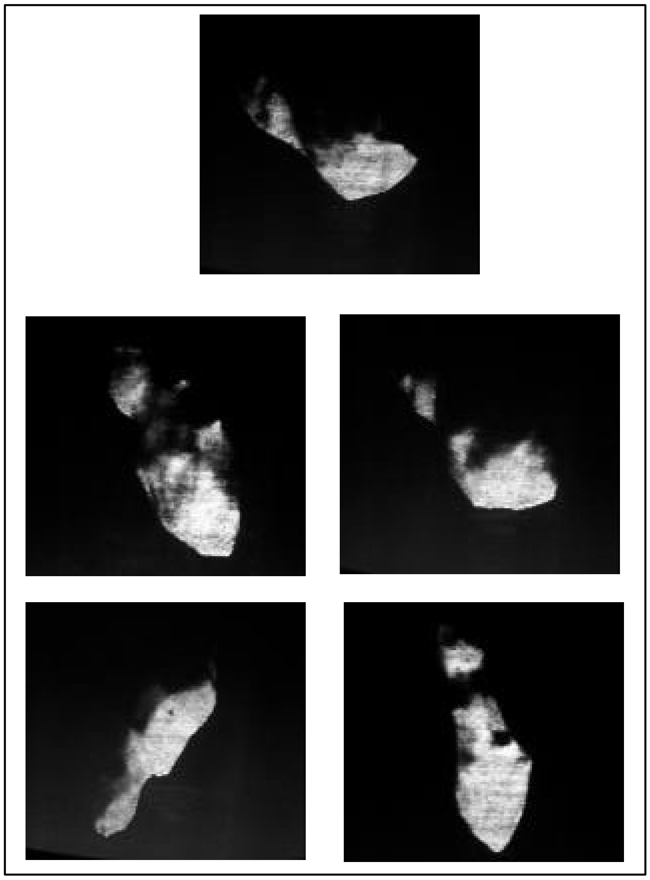

Figure 5. Experimental results showing retrieved holographic images of a Toutatis Asteroid.